UPSTREAM EFFECTS OF SECONDARY INJECTION ON THE PROFILES OF A BOUNDARY LAYER OVER A FLAT PLATE

A THESIS

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BY

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PREFACE

An account is given of the effect on the boundary layer of a secondary air flow directed normal to a flat plate immersed in a primary flow field of uniform velocity. System design and tunnel operation are discussed briefly. Boundary layer profiles are compared to existing theory and secondary injection effects are discussed.

The work described in this thesis was initiated by the author following exposure to the field of jet interaction. Boundary layer conditions during portions of flight where the airstream is subsonic and jet interaction is the means of control posed the problem considered herein.

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1. INTRODUCTION

The purpose of this work was to study experimentally the effects of injecting a subsonic airstream into another subsonic airstream such that boundary layer changes in the primary airstream over a flat plate will occur thus altering the flow characteristics throughout the flow field.

In 1970, an initial request for information concerning high speed, high angle of attack flight was made to the major industries concerned with aeronautics and astronautics. One conclusion of industry at that time was that for high speed flight greater than 3000 fps conventional airfoils on control systems produced excessive drag and therefore a different control concept would be required especially at high angles of attack. One such control concept presented was Thrust Vector Control (TVC). Here the secondary airstream would be injected into the exhaust nozzle of the rocket motor producing a sideward force on the missle body. For TVC mass flow ratios $(\dot{m}_i/\dot{m}_\infty)$ can vary over a wide range of values. However, for a given system with flows of constant density with respect to time, the mass flow ratio $(\dot{m}_i/\dot{m}_\infty)$ can be reduced to:

$$\text{constant}\ \left(\frac{v_i}{v_\infty}\right)$$

where (v_i/v_∞) will be dependent on v_∞ or the physical location of the injection slot in the exhaust since v_i is normally sonic velocity. TVC would then have values of $(v_i/v_\infty) < 1.0$. A practical limit exists for angle of attack control, however, and TVC was considered a good solution for only small control corrections. Another concept recommended was Jet Interaction (JI) which like TVC requires the injection of one airstream

into another, but unlike TVC, uses injection into the main flow about the body itself. JI mass flow ratios also can vary over a wide range of values with v_i/v_∞ characteristically greater than 1.0 . From a control standpoint, there would be no limitation on missile body angle of attack and as the flight Mach number increases the side force gained from the secondary injection would also increase.

Most experimental work has been done with supersonic JI models. Several models have been proposed making use of the continuity and momentum equations to explain the data attained. Experimentally, fair agreement has been reached for the different models. However, little is known of the actual velocity profiles surrounding a secondary jet and some of the model assumptions, though giving fair results, do not seem very practical. High speed control then by JI is in the future and will require much more development.

An interesting aspect of JI is low speed control which would be required at launch for a very short time and possibly for longer periods of time just prior to termination. Use of JI would eliminate effective aerodynamic controls. Without control surfaces the JI system, though uneconomical from a control force standpoint, would have to be made compatible and useful in this flight regime.

Subsonic JI is presently presented under the broad concept of V/STOL and has in most cases been neglected from experimental work because of the lack of an amplification factor. A closer look is warranted for subsonic JI particularly into the areas of mixing between the various airstreams, propagation of disturbances in the primary airstream, boundary layer separation in the primary airstream and the actual velocity profiles in the

flow fields associated with both the primary and secondary airstreams. References 1 through 3 deal with the particular problems previously discussed.

The work contained here was limited to some simple aspects of the effect on a boundary layer in the subsonic injection problem.

Both the primary flow field and the secondary flow field were limited to approximately Mach 0.2 or the incompressible flow region. The region studied extended forward from the secondary injection slot to the leading edge of the flat plate.

2. APPARATUS AND TECHNIQUE

Primaryair for this work was supplied by the Stanford Low Speed Wind Tunnel located in the William F. Durand Building constructed in 1970 by Inca Engineering Corporation of San Gabriel, in conjunction with the Aeronautics and Astronautics Department. This closed loop wind tunnel has a contraction ratio of nine and is powered by anaxivane fan with electric variable pitch which produces a maximum velocity of approximately 238 fps. The test section is completely removable and has a square cross section 18 inches on a side and an overall length of 35½ inches. A pitot-static system is installed in the test section to allow for speed monitoring. Velocity variation time was found to be negligible and free stream turbulence was estimated at approximately 0.4%.

Flat plate design was based mainly on the predicted Reynolds Number of the primary airstream flowing over the flat plate and the attainable velocity profile of the secondary airstream. Plexiglas was selected for the flat plate for ease of handling and machining. Initial predicted values of Reynolds Number indicated a variation of Re_x from 4.0×10^5 per foot at 67 fps to 8.9×10^5 per foot at 150 fps. The critical R_e was therefore reached in the first 12 inches of travel on the plate.

Seconday air was supplied to the flat plate from the high pressure air system in the Durand Building and monitored through a Norgren pressure regulator and dryer and another Victor pressure regulator for flow stability purposes. Initial building system pressure varies from 80 to 100 psi. With use of the two regulator system, this pressure was stabilized and reduced to a maximum of 60 psi.

The secondary air flow system consisted of a three inch deep cylindrical plenum mounted to the underside of the plate. Quarter inch copper tubing was used to supply the plenum with air from the high pressure air system. Plenum design was such that a plexiglas plug formed the cover to the plenum as shown in Figure 1 and allowed use of various plugs without constructing another plate. The plenum accepted the high pressure air through a fine mesh screen and discharged the flow through another screen at the mouth of the plate plug slot .183 inches in width. Steel wool was used to baffle the flow through the plenum.

The hot wire electronics package shown in Figures 2 and 3 was designed at The Naval Postgraduate School and required only operational calibration for direct use in boundary layer measurement. The direct reading gage incorporated in the electronic package presented an RMS voltage output. The output could also be presented with a digital voltage readout or oscilloscope display, whichever is preferable.

Speeds for the primary air flow for the tests were selected at 67 fps, 103 fps, and 150 fps, representing a pure laminar flow, a flow critical at the injection point and a turbulent flow over much of the plate. The injection slot (Figure 4) was placed 6 inches from the sharp leading edge of the plate to ensure the above conditions. Irregularities over the plate due to variation of thickness of the plexiglas were considered to have negligible adverse effect on the test data. The flat plate was designed to span the entire tunnel cross-section and therefore used the tunnel test section walls as end plates to ensure two-dimensional flow over the flat plate. Vertically, the flat plate was placed so that the primary air flow had 9 inches of depth to ensure avoidance of wall boundary layer

profiles. The flat plate extended into the expansion section of the wind tunnel for support purposes as well as to ensure a lack of feedback from the under surface of the plate. Secondary air flow speed increments of 50 fps were used from zero to 200 fps spanning the range of pressures available and the two-dimensionality of the slot.

Vertical position above the plate (y) was calculated as follows: The hot wire probe was inserted through a single hole directly above the flat plate. An actual scale template was drawn for the model, test section, and probe. Angular position and extension of the probe outside the tunnel was then correlated to the template to give the actual location of the hot wire relative to the plate model.

Calibration of the flow fields was conducted in the following manner. The Hot Wire was calibrated in a known flow field prior to being used in the test. With an accurated curve of voltage versus velocity available at a given temperature, the Hot Wire was then placed in the primary flow field where velocity could be compared to that given by a pitot-static probe. From this information velocity deviation due to temperature change was available. After the Hot Wire was calibrated, the secondary flow was calibrated so that a given output pressure produced a required velocity at the slot. Secondary air flow was found to be constant over 87% of the slot or about 1 3/4 inches. Profiles along the plate centerline therefore insured two-dimensional flow.

Primary air flow calibration was not easily attained. It was found that, through normal wind tunnel operation, the static temperature in the tunnel could rise as much as 16^{o}F. Therefore, after calibrating the hot wire through many speed cycles a group of calibration curves were attained

which allowed for continual recalibration through the test program.

The test procedure consisted of multiple speed variations with the primary air flow varied as 67 fps, 103 fps, and 150 fps. Secondary air flow speed increments of 50 fps were used from zero to 200 fps. Boundary layer profiles were then taken at 5 stations located between the leading edge of the flat plate and the leading edge of the injection slot. Boundary layer theory and comparison was then used to complete the study.

3. BOUNDARY LAYER PROFILES WITHOUT INJECTION

From Schlichting[4] we find that the boundary layer thickness varies for the laminar and turbulent flow regimes. For the laminar flow region or Re below 3.2×10^5, the boundary layer thickness is given by:

$$\delta = 5\sqrt{\frac{v\ell}{U}}$$

where v = kinematic viscosity

ℓ = a reference length

U = free stream velocity.

In this work ℓ is defined as x-the distance from the leading edge of the flat plate. Then it can be seen that for laminar flow at a constant velocity

$$\delta \sim \text{Constant} \sqrt{x}$$

or as represented in Schlichting

$$\frac{\delta}{x} \sim \text{Constant } x^{-\frac{1}{2}}$$

This relationship was used to verify profiles attained over the entire flow field at $U_\infty = 67$ fps and over the laminar sections of the flow fields for the higher free stream velocities.

For turbulent flow the relationship for boundary layer thickness is changed somewhat. Schlichting presents the relation for turbulent flow as:

$$\delta = .37\ell(Re_\ell)^{-1/5} = .37(\frac{v}{U})^{1/5} x^{4/5}$$

Again, recognizing that at a particular constant free stream velocity:

$$\frac{\delta}{x} \sim \text{Constant } x^{-1/5}$$

With the use of these laminar and turbulent relations, the two-dimensional boundary thickness growth profiles attained from the leading edge of the flat plate to the leading edge of the slot were verified to within a small constant over the entire span of free stream velocities. From Figure 5 the following summary chart depicts the condition of the primary flow over the flat plate at the various stations.

ft/sec U_∞	1/ft $Re_x \times 10^{-5}$	Condition of Primary Flow (Stations) 1	2	3	4	5	6
67	4.0	Lam	Lam	Lam	Lam	Lam	Lam
103	6.1	Lam	Lam	Lam	Lam	Lam	*Lam
150	819	Lam	Lam	Lam	Turb	Turb	Turb

*Critical x calculated.

A further plot of the laminar boundary layer profile in the form of η versus U/U_∞ where

$$\eta = y\sqrt{\frac{U_\infty}{v_x}}$$

agreed to within a small constant of the results gained by Nikuradse for laminar flow over a wide range of Re .

Conditions for flow comparison with Schlichting were limited to the cases for each free stream velocity with no secondary injection. These conditions were in agreement with Schlichting and were then used as the

basis for the remainder of the study. With the secondary injection imposed on the free stream, the changss resulting in the boundary layer could then be correlated to these initially known conditions.

The small deviation constant referred to above was attributed to an angle of attack on the flat plate. Since relative changes only were required, this condition was not considered detrimental to the experiment.

4. SECONDARY INJECTION EFFECTS

Secondary injection produced a pronounced increase in the boundary layer profile at the various stations selected along the plate.

The data attained resembled Figure 6 for each station and for the various ratios of injected velocity to free stream velocity (U_i/U_∞). Schlichting defines the boundary layer thickness as the point at which a 1% velocity difference appears relative to the external or free stream velocity. This point is rather difficult to attain and therefore it was decided to use a 5% velocity differential to define a boundary layer height. The induced error would be constant over the entire boundary layer field but would be minimized by plotting the change in boundary layer thickness caused by the secondary injection normalized by the initial boundary layer height for trend purposes.

Referring to Figure 6, it can be seen that the actual profiles, while unchanged at stations two and three, are greatly effected at stations four, five, and six. In this example, case $U_i/U_\infty = 2.24$. The complete tests over the range of U_i/U_∞ of zero to 3.0 gave profiles of similar orientation. By correlating changes in the boundary layer profile at a constant free stream velocity with changing secondary injection velocity with changes in the boundary layer profile at a constant secondary injection velocity with changing free stream velocity, the upstream propagation point could be realized.

From Figure 7, certain conclusions can be reached. For a free stream velocity of 67 fps or laminar flow the upper curve indicates that as the injected velocity is increased, the effects of this secondary injection

are propagated toward the leading edge of the plate.

For the case where the flow was very nearly at critical Re over the distance from the leading edge of the slot to the leading edge of the plate, it can be seen that the actual point at which effects are felt upstream does not vary appreciably.

For turbulent flow, as the injection velocity is increased the propagation effects move toward the leading edge of the plate. The significance of this profile shift is that only a small injection will effect both laminar and turbulent flow upstream, however, only a small injected velocity will propagate much further forward in turbulent flow than in laminar flow. The effects of an injection velocity $U_i/U_\infty = .33$ show that the propagation point is over half the distance to the leading edge while an injection velocity $U_i/U_\infty > 3.0$ is required to gain the same effects in laminar flow.

From Figure 8, for the various injected velocity ratios, it is seen that the actual increase in boundary layer height was nearly independent of Re. For the various stations tested at one inch intervals from the leading edge it is noted that boundary layer thickness increases as much as 150% over the boundary layers verified by comparison with Schlichting.

From the profiles as in Figure 6, a summary can be made of the flow conditions along the plate. Noting that several conditions can exist, they are abbreviated as follows:

L - Laminar Flow

TT - Transition to turbulent flow

T - Turbulent Flow

LS - Laminar Separation

S - Separation

Difficulty existed in finding the modes of separation since the measured stations were one inch apart. However, from profile examination at individual stations as well as from boundary layer thickness trends along the plate the summary chart represents the flow field that existed.

U_∞	U_i	Stations 1	2	3	4	5	6
67	0	L	L	L	L	L	L
	50	L	L	L	TT	T	T
	100	L	L	L	LS*	S	S
	150	L	L	LS*	S	S	S
	200	L	L	LS*	S	S	S
103	0	L	L	L	L	L	L
	50	L	L	TT	T	T	T
	100	L	L	TT	T	T	T
	150	L	L	TT	T	T	T
	200	L	TT	T**	TS	S	S
150	0	L	L	L	TT	T	T
	50	L	L	TT	T	T	T
	100	L	L	TT	T	T	T
	150	L	L	TT	T	T	T
	200	TT	T	T	T	T	T

*Unable to discern if turbulent transition takes place prior to separation.

**Transition shown and appears to follow pattern shown.

5. CONCLUDING REMARKS

The boundary layer on a flat plate is effected by a secondary stream injected at some point on the plate in subsonic flow. The effects are propagated forward in the primary flow and the boundary layer grows to accept a smooth transition to a mixed profile of the primary and secondary flows. The thickness growth appears to be independent of Re in incompressible flow while the actual upstream point at which the propagation is felt depends on the nature of the flow. Turbulent flow effects were felt further upstream for the same secondary injection.

Further research for the range of Mach where compressibility effects occur would be desirable to bridge this work with work done by many others in the sonic, supersonic, and hypersonic fields. Flow visualization would also be desirable to verify mixing theory and model prototypes that could be used to duplicate this work.

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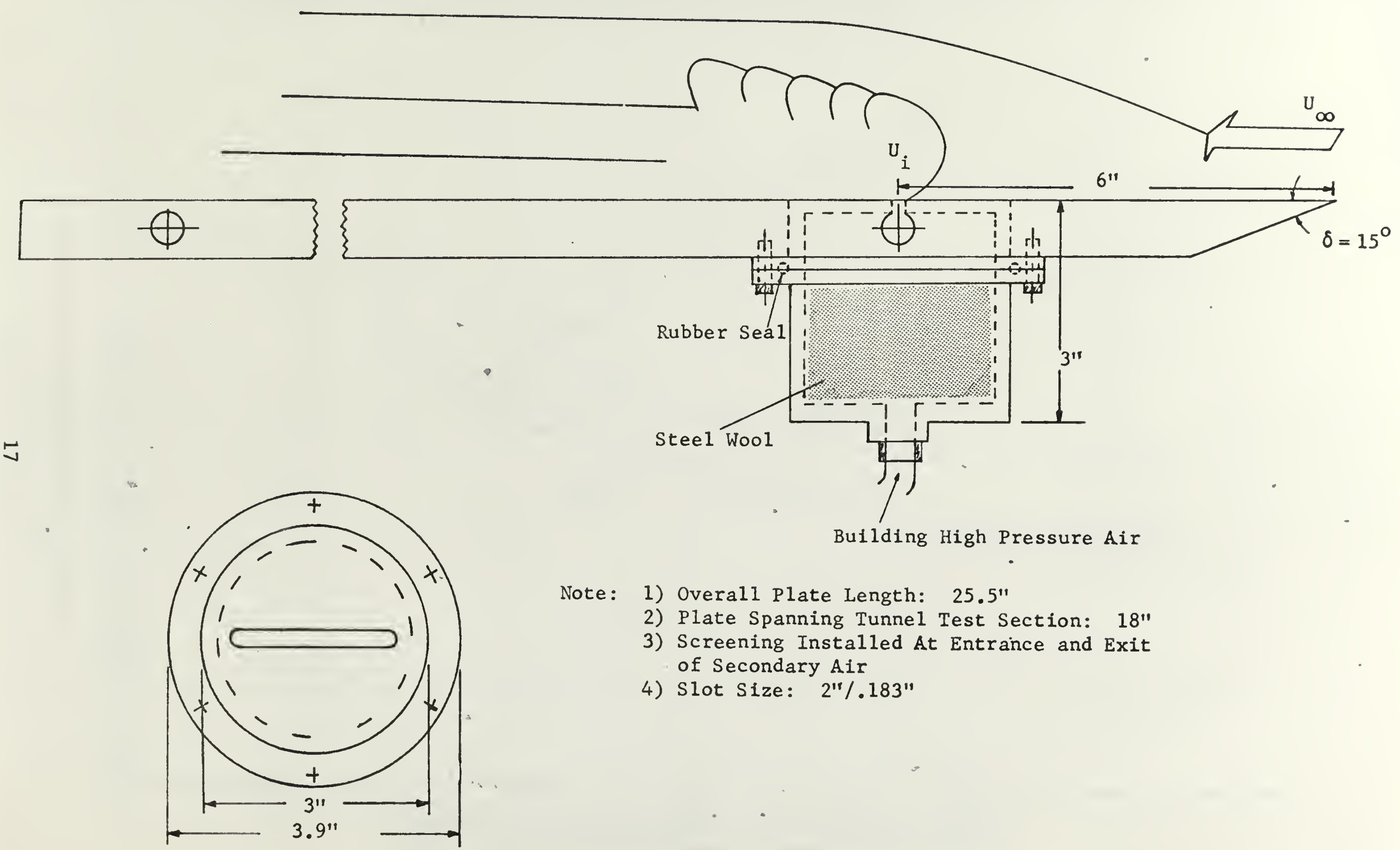

FIG. 1. Flat Plate with Secondary Air Plenum.

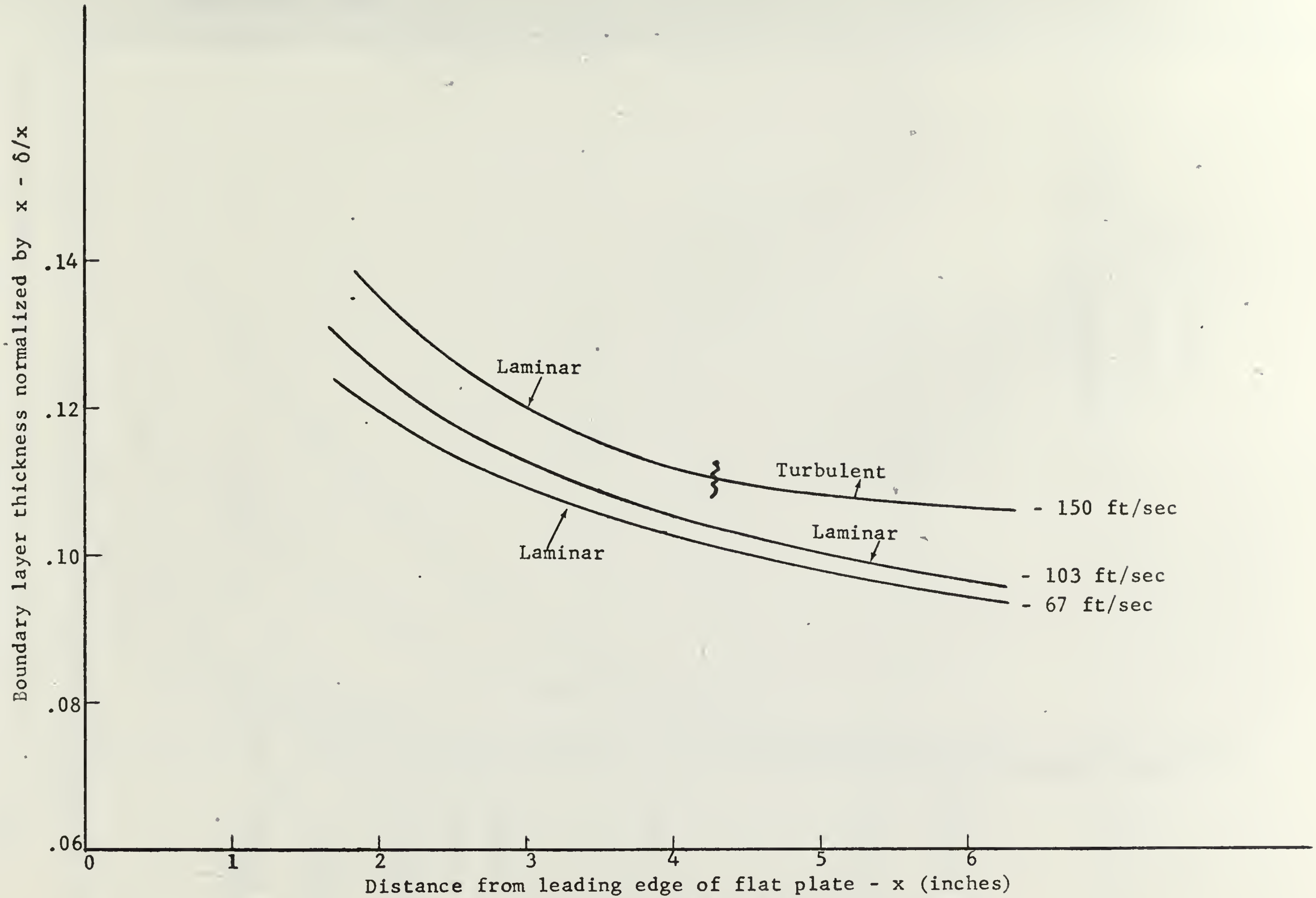

FIG. 5. No Injection Boundary Layer Profile Growth.

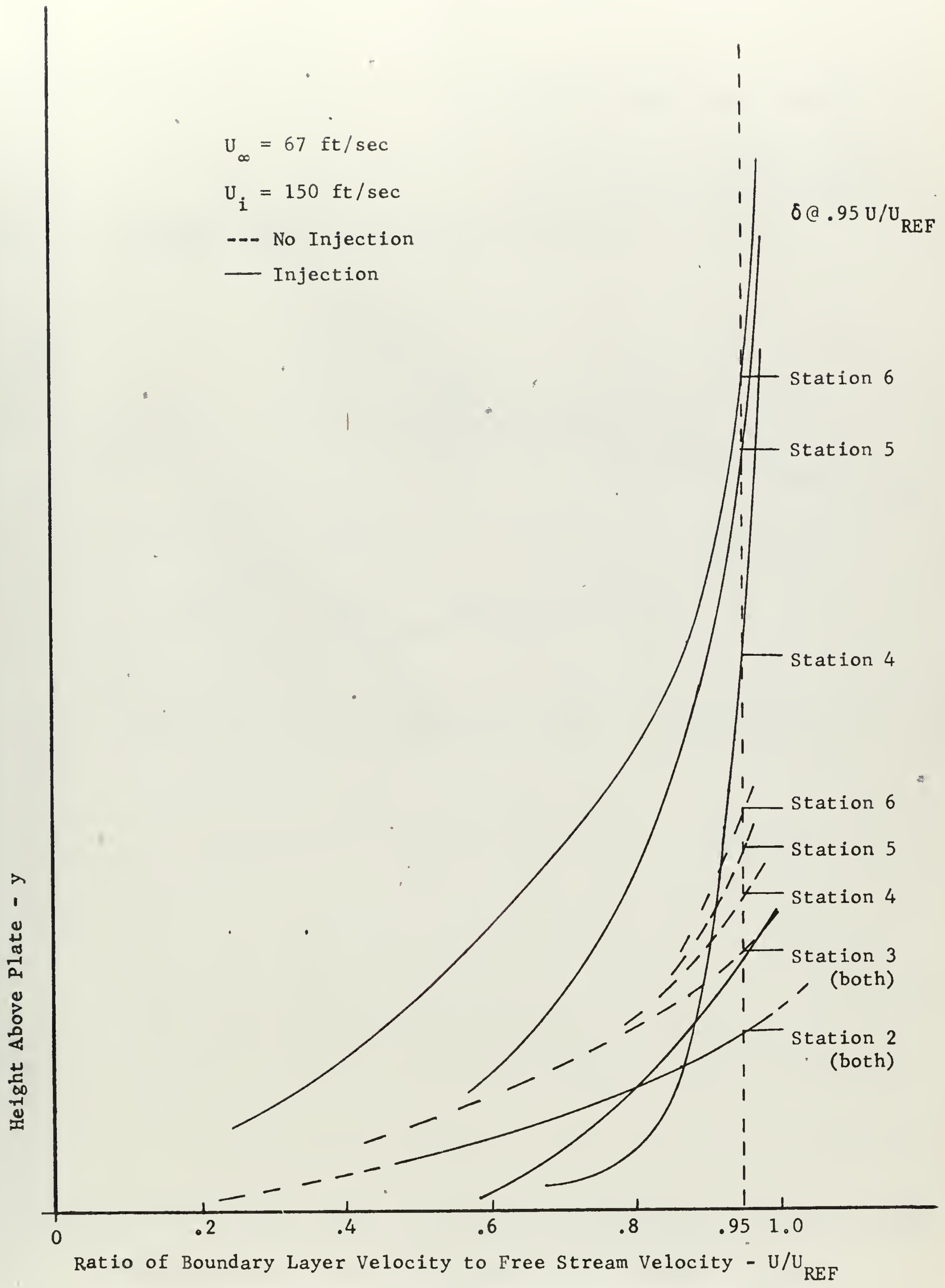

FIG. 6. Boundary Layer Profile

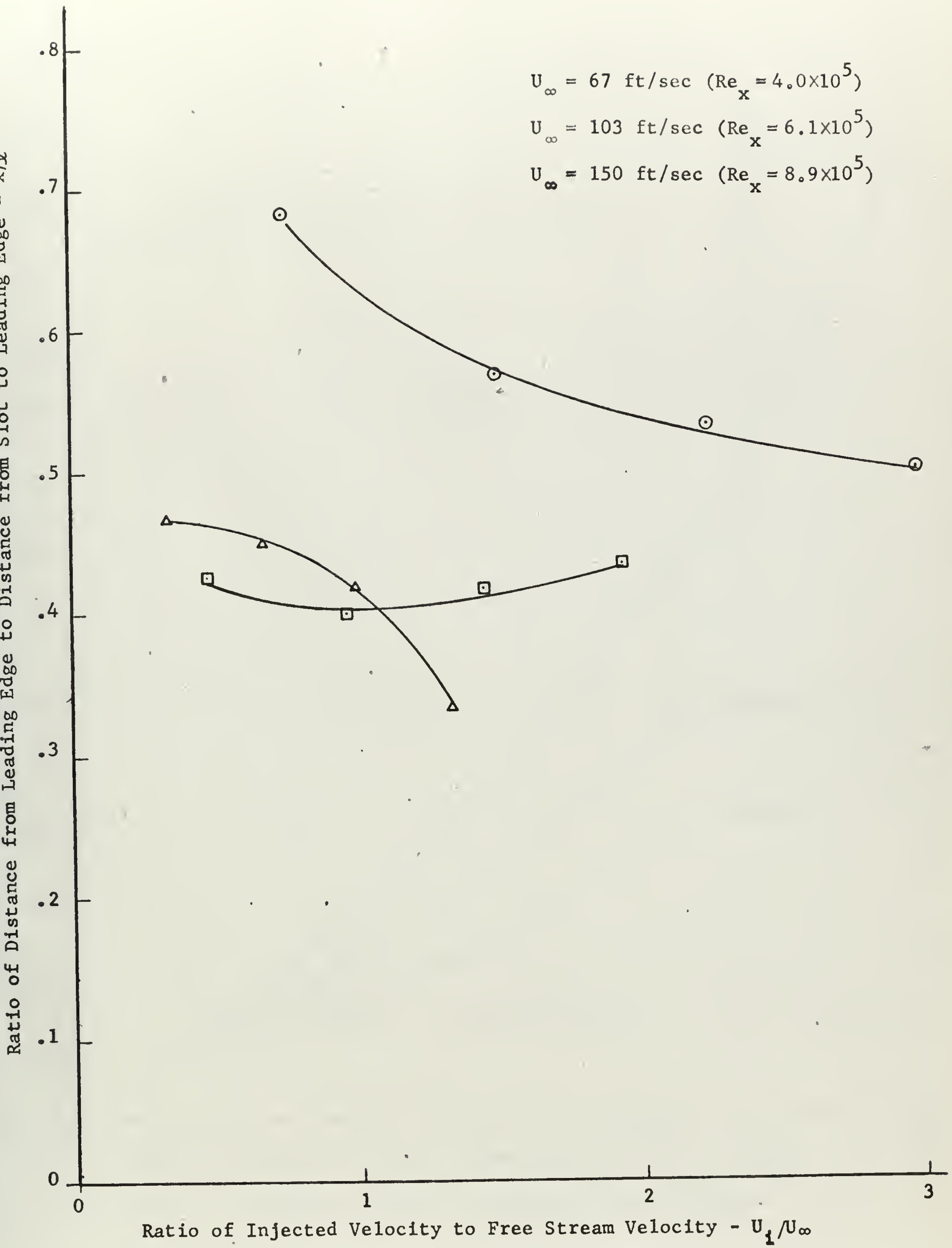

FIG. 7. Forward Propagation of Effects Felt in Boundary Layer.

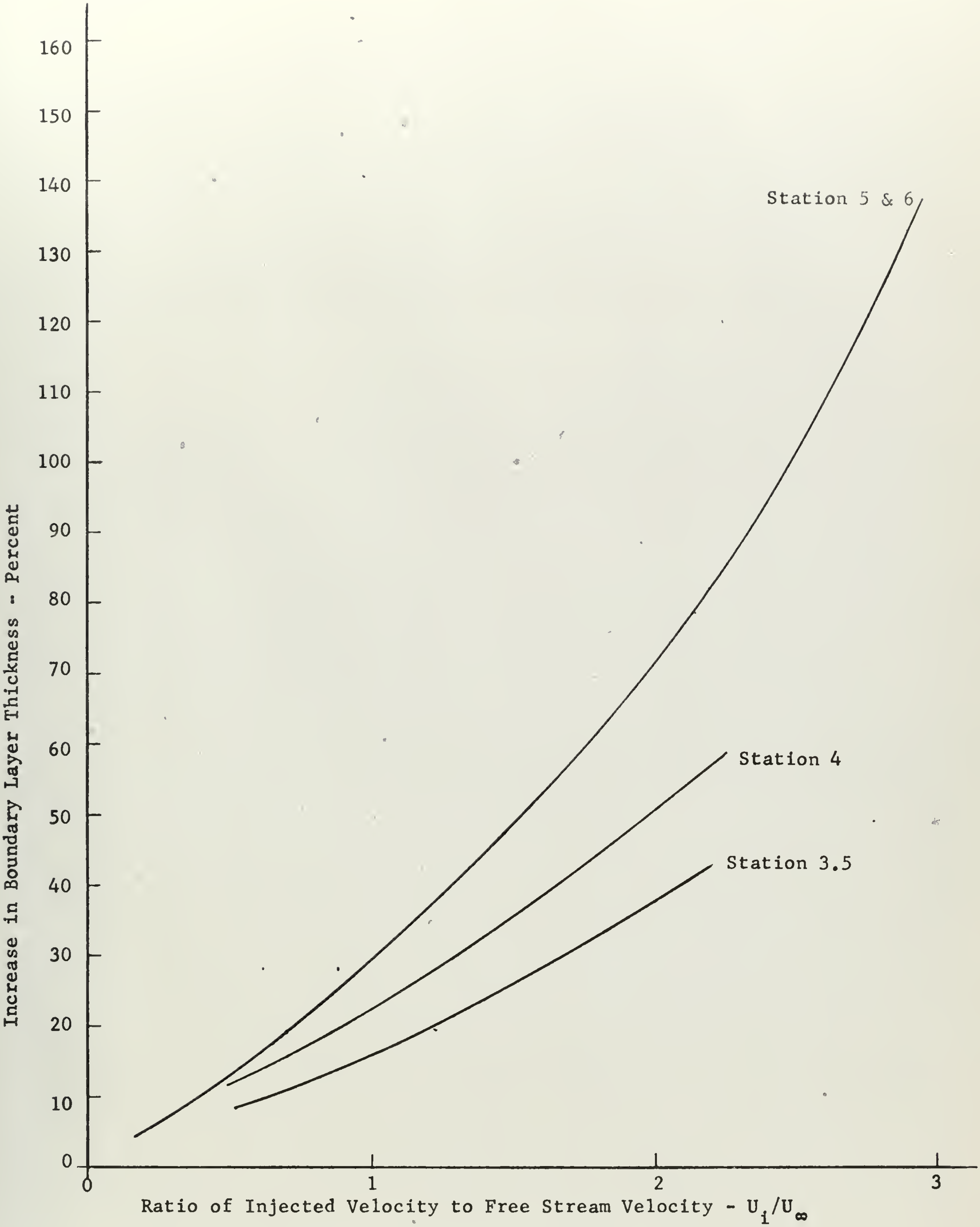

FIG. 8. Percentage Increase in Boundary Layer Thickness

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